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Suppression factors in diffractive photoproduction of dijets

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Abstract

After new publications of H1 data for the diffractive photoproduction of dijets, which overlap with the earlier published H1 data and the recently published data of the ZEUS collaboration, have appeared, we have recalculated the cross sections for this process in next-to-leading order (NLO) of perturbative QCD to see whether they can be interpreted consistently. The results of these calculations are compared to the data of both collaborations. We find that the NLO cross sections disagree with the data, showing that factorization breaking occurs at that order. If direct and resolved contributions are both suppressed by the same amount, the global suppression factor depends on the transverse-energy cut. However, by suppressing only the resolved contribution, also reasonably good agreement with all the data is found with a suppression factor independent of the transverse-energy cut.

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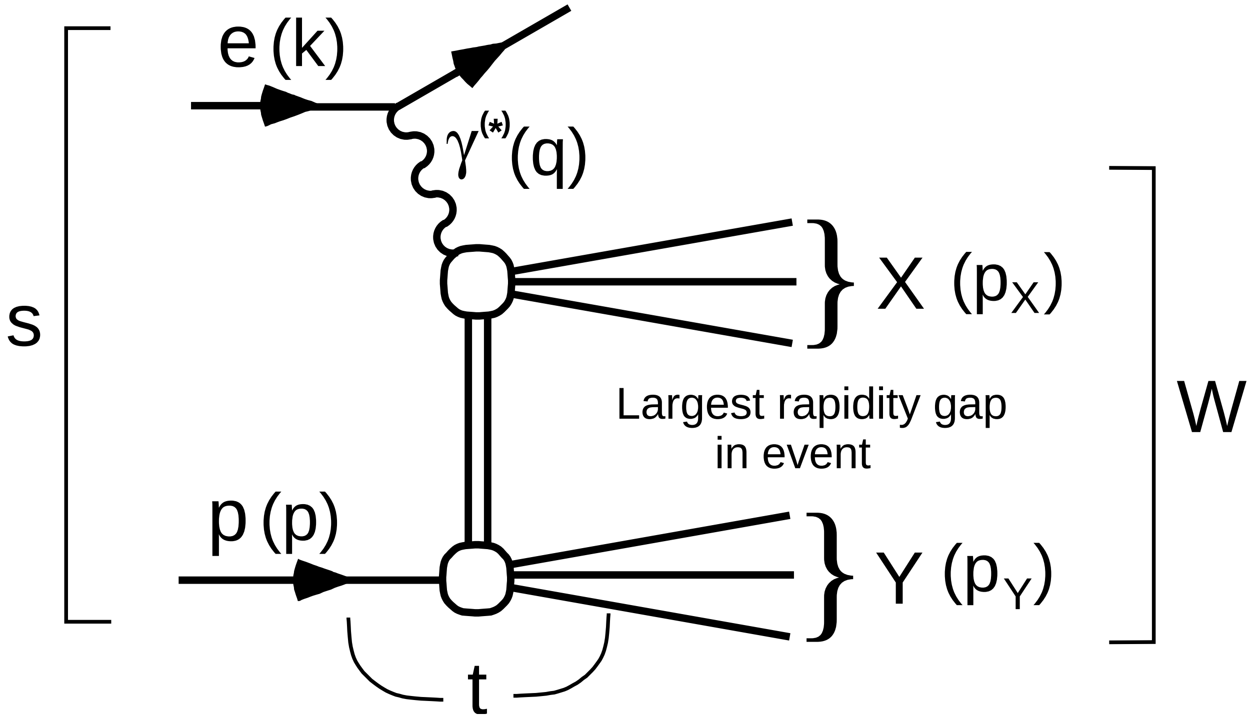

FIG. 1: Diffractive scattering process $ep \to eXY$, where the hadronic systems X and Y are separated by the largest rapidity gap in the final state.

I. INTRODUCTION

At high-energy colliders such as the ep collider HERA at DESY and the $p\bar{p}$ collider Tevatron at Fermilab, diffractive processes are known to constitute an important fraction of all scattering events. These events are defined experimentally by the presence of a forward-going hadronic system Y with four-momentum p_Y, low mass M_Y (typically a proton that remained intact or a low-lying nucleon resonance), small four-momentum transfer $t = (p - p_Y)^2$, and small longitudinal momentum transfer $x_{I\!P} = q(p - p_Y)/(qp)$ from the incoming proton with four-momentum p to the central hadronic system X (see Fig. 1 for the case of $ep \to eXY$). Experimentally a large rapidity gap separates the hadronic system X with invariant mass M_X from the final-state system Y.

Theoretically diffractive interactions are described in the framework of Regge theory [1] as the exchange of a trajectory with vacuum quantum numbers, the Pomeron ($I\!P$) trajectory. Then the object exchanged between the systems X and Y, as indicated in Fig. 1, is the Pomeron (or additional lower-lying Regge poles), and the upper vertex of $ep \to eXY$, i.e.

$e\mathbb{P} \to eX$, can be interpreted as deep-inelastic scattering (DIS) on the Pomeron target for the case that the virtuality of the exchanged photon $Q^2 = -q^2$ is sufficiently large. In analogy to DIS on a proton target, $ep \to eX$, the cross section for the process $e\mathbb{P} \to eX$ in the DIS region can be expressed as the convolution of partonic cross sections and universal parton distribution functions (PDFs) of the Pomeron. The partonic cross sections are the same as for ep DIS. The Pomeron PDFs are usually multiplied with vertex functions for the lower vertex in Fig. 1, yielding the diffractive parton distribution functions (DPDFs). The Q^2 evolution of the DPDFs is calculated with the usual DGLAP [2] evolution equations known from $ep \to eX$ DIS. Except for the Q^2 evolution, the DPDFs can not be calculated in the framework of perturbative QCD and must be determined from experiment. Such DPDFs [3–6] have been obtained from the HERA inclusive measurements of the diffractive structure function F_2^D [3, 4], defined in analogy with the proton structure function F_2.

The presence of a hard scale such as the squared photon virtuality $Q^2 = -q^2$ in deep-inelastic scattering or a large transverse jet energy E_T^{jet} in the photon-proton center-of-momentum frame should then allow for calculations of partonic cross sections for the central system X using perturbative QCD. Such diffractive processes with the presence of a hard scale are usually called hard diffractive processes. The central problem in hard diffraction is the problem of QCD factorization, i.e. the question whether diffractive cross sections are factorisable into universal diffractive parton density functions and partonic cross sections.

For DIS processes, factorization has indeed been proven to hold [7], and DPDFs have been extracted at low and intermediate Q^2 [3, 4] from high-precision inclusive measurements of the process $ep \to eXY$ using the usual DGLAP evolution equations. The proof of the factorization formula, usually referred to as the validity of QCD factorization in hard diffraction, also appears to be valid for the direct part of photoproduction $Q^2 \simeq 0$ or low-Q^2 electroproduction of jets [7]. However, factorization does not hold for hard processes in diffractive hadron-hadron scattering. The problem is that soft interactions between the ingoing hadrons and their remnants occur in both the initial and final states. This agrees with experimental measurements at the Tevatron [8]. Predictions of diffractive dijet cross sections for collisions as measured by CDF using DPDFs determined a few years ago [9] and more recently [4] by the H1 collaboration at HERA overestimate the measured cross section by up to an order of magnitude [8, 10]. This suppression of the CDF cross section can be explained by the rescattering of the two incoming hadron beams which, by creating

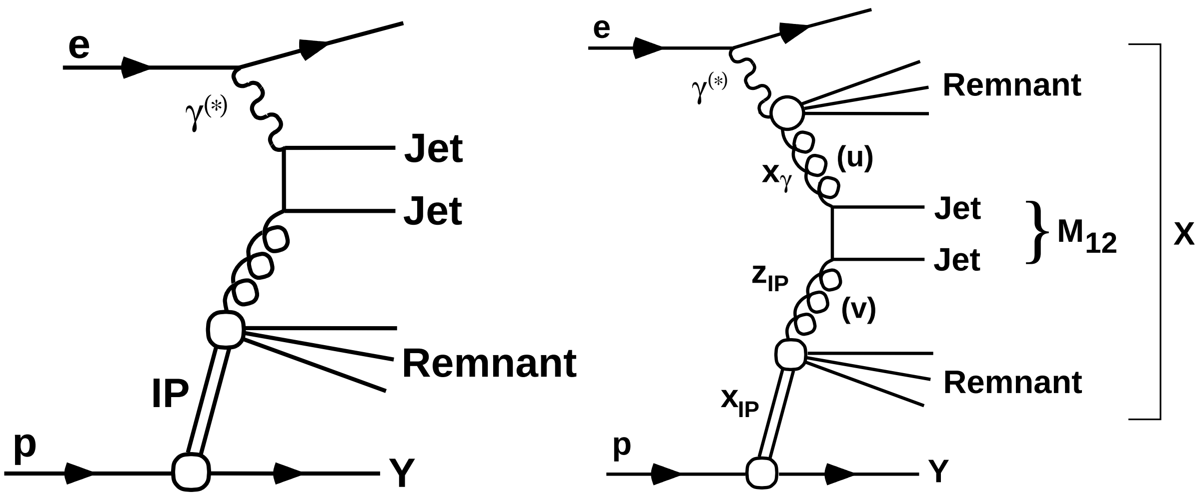

FIG. 2: Diffractive production of dijets with invariant mass M_{12} in direct (left) and resolved (right) photon-pomeron collisions, leading to the production of one or two additional remnant jets.

additional hadrons, destroy the rapidity gap [11]. Jet production with real photons involves direct interactions of the photon with quarks or gluons from the proton (or in our case from the pomeron) as well as resolved photon contributions, leading to parton-parton interactions and an additional remnant jet coming from the photon as reviewed in [12] (see Fig. 2). For the direct interactions, factorization is expected to be valid as in the case of DIS, whereas we expect it to fail for the resolved process as in hadron-hadron scattering. For this part of photoproduction one would therefore expect a similar suppression factor due to rescattering effects of the ingoing partons. Introducing vector-meson dominance photon fluctuations, such a suppression by about a factor of three for resolved photoproduction at HERA was predicted [13].

On the experimental side, the first measurements of dijet cross sections in diffractive photoproduction have been presented by the H1 collaboration as contributions to two conferences [14]. The kinematic range for these data were $Q^2 < 0.01$ GeV^2, $x_{I\!P} < 0.03$, $E_T^{jet1} > 5$ GeV, $E_T^{jet2} > 4$ GeV and $165 < W < 240$ GeV, where jets were identified using the inclusive k_T-cluster algorithm. The measured cross sections as a function of x_γ^{obs} and $z_{I\!P}^{obs}$ were compared to leading-order (LO) QCD predictions, using the RAPGAP Monte Carlo model [15]. For the DPDFs the LO 'H1 2002 fit' was used [9]. It was found that these two cross sections were well described by the predictions in normalization and shape over the whole range of x_γ^{obs} and $z_{I\!P}^{obs}$, showing no breakdown of factorization in either the resolved or in the

direct photoproduction. In addition, normalized cross sections as a function of various other variables were compared to the predictions with the result that all measured distributions were in good agreement.

Subsequently we calculated the next-to-leading order (NLO) corrections for the cross section of diffractive dijet production using the same kinematic cuts and with the same DPDFs as in the first H1 analysis [14] on the basis of our previous work on NLO corrections for inclusive direct [16] and resolved [17] dijet photoproduction. While at LO good agreement with the H1 data [14] was found, consistent with the finding in the H1 analysis [14], it was found that the NLO corrections increase the cross section significantly [18, 19] and require a suppression factor of the order of $R = 0.5$. Since on theoretical grounds only a suppression of the resolved cross section would be acceptable, we demonstrated in [18, 19] that by multiplying the resolved cross section with a suppression factor of $R = 0.34$, reasonably good agreement with the preliminary H1 data [14] could be achieved. This value for the suppression factor turned out to be in good agreement with the prediction of [13].

The first experimental data from the ZEUS collaboration were presented at the DIS workshop in 2004 [20]. The dijet cross sections were obtained in the kinematic range $Q^2 < 1$ GeV^2, $x_{I\!P} < 0.025$ and $E_T^{jet1(2)} > 7.5$ (6.5) GeV. For these kinematic constraints NLO calculations were not available in 2004. So, the measurements were compared to LO calculations, unfortunately with previous H1 DPDFs [21] with the result that good agreement in the shape was achieved. However, the normalization was off by a factor of 0.6, which was attributed later to the older DPDF input [22], so that the H1 and ZEUS results were consistent with each other. The situation concerning the agreement of H1 and ZEUS data and the influence of NLO corrections improved already considerably in the fall of 2004. At the ICHEP 2004 both collaborations presented their new data and compared them with NLO cross section calculations. H1 compared their data with the predictions from the program of Frixione [23] and ZEUS with our calculations along the lines of [18, 19], where now only the different kinematic cuts of the ZEUS analysis had to be incorporated. Both collaborations also used the same DPDFs, namely the 'H1 2002 fit' [9]. The conclusion from the comparison of the respective NLO calculations with the H1 [24] and ZEUS [25] measurements were very similar. Both collaborations observed from their data that good agreement was achieved with the global suppression (of direct and resolved contribution) by a factor 0.5. Concerning the model with suppression of the resolved contribution only, the H1 collaboration concluded

that this model was disfavored compared to the global suppression model. This result was obtained by comparing the differential cross sections $d\sigma/dx_\gamma^{obs}$ and $d\sigma/dy$ to a calculation, in which the partonic cross sections were suppressed for $x_\gamma^{obs} < 0.9$ by a factor of $R = 0.34$. In the ZEUS contribution to the ICHEP 2004, differential cross sections of several observables had been shown and compared with our calculations. All five comparisons, namely for y, $x_{I\!P}$, $z_{I\!P}^{obs}$, E_T^{jet1} and η^{jet1}, showed very good agreement both in shape and normalization of the cross section with the resolved photon suppression ($R = 0.34$). The only exception was the comparison of $d\sigma/dx_\gamma^{obs}$, which did not show agreement with the resolved photon suppression only. Here the suppression factor varied as a function of x_γ^{obs} between 0.5 and 0.75 and the description of the shape was better without any suppression, which would signal a global suppression. We emphasize that at this stage of the analysis at the end of 2004, both the H1 [24] and ZEUS [25] collaborations showed that their data were consistent with a global suppression of about a factor of two against the sum of direct and resolved NLO QCD predictions. In addition, in the H1 contribution [24] it was claimed explicitly that there was evidence for factorization breaking also in direct photoproduction. In 2005 the ZEUS collaboration presented a more detailed comparison by dividing their data sample into two subsets, $x_\gamma^{obs} > 0.75$ and $x_\gamma^{obs} < 0.75$, in order to be more sensitive to the suppression of the direct ($x_\gamma^{obs} > 0.75$) and the resolved ($x_\gamma^{obs} < 0.75$) components. Together with the result of H1 the overall conclusion at the DIS 2005 workshop was the same as at the end of 2004, namely, that good agreement was achieved with the global suppression of 0.5, while a suppression of only the resolved contribution at NLO was disfavored by the data [26].

The analysis of the ZEUS data with respect to the samples enriched in direct and resolved processes was continued in a contribution to the Uppsala Lepton-Photon conference in 2005 [27]. For $x_\gamma^{obs} > 0.75$ the NLO predictions gave a good description of the shape of the measured cross section, although the absolute normalization was a factor of two above the data. For $x_\gamma^{obs} < 0.75$ the NLO calculations were again above the data when no suppression ($R = 1$) was applied and below the data by a factor of two when a suppression with $R = 0.34$ was applied to the resolved photon processes. The ratio of the resolved-enriched to the direct-enriched samples was reasonably well reproduced by the NLO predictions with $R = 1$, indicating that a suppression of the resolved sample with respect to the direct sample was not seen in any particular kinematic region. This agreed with the earlier findings that a uniform suppression for both resolved and direct process gives a better description of the

data. Of course, all these conclusions relied on the fact, that the DPDFs as evaluated by H1 [9] are really the correct ones. The analysis in [27] was based on the largest selection of variables so far, namely $y, x_{I\!P}, M_X, z_{I\!P}^{obs}, E_T^{jet1}$ and η^{jet1}.

The conclusions above concerning the global overall suppression versus a suppression in the resolved contribution only based solely on preliminary data from H1 and ZEUS and the preliminary 'H1 2002 fit' [9] for the DPDFs remained also after 2005 until the final publications of the H1 and ZEUS analysis appeared in 2007. The comparison between the final experimental results and the NLO theory used the new and final DPDFs constructed by the H1 collaboration [4]. This analysis was based on the larger sample of the years 1997-2000 as compared to the previous published PDF sets. In [4] two NLO fits, 'H1 2006 fit A' and 'H1 2006 fit B' were presented, which both give a good description of inclusive diffraction. These two sets of PDFs differ mainly in the gluon density at large fractional parton momentum, which is poorly constrained by the inclusive diffractive scattering data, since there is no direct coupling of the photon to gluons, so that the gluon density is constrained only through the evolution. The gluon density of fit A is peaked at the starting scale at large fractional momentum, whereas the fit B is flat in that region.

The differential cross sections as measured in diffractive photoproduction by H1 [28] were compared with the NLO predictions obtained with the Frixione program [23], interfaced to the 'H1 2006 fit B' DPDFs. In this publication [28], the conclusions deduced earlier from the comparison with the preliminary data and the preliminary 'H1 2002 fit' [9] are fully confirmed, now also with the new DPDF fits [4]. In particular, the global suppression is obtained, independent of the DPDF fits used, i.e. fit A or fit B, by considering the ratio of measured dijet cross section to NLO predictions in photoproduction in relation to the same ratio in DIS. In this comparison the value of the suppression is 0.5 ± 0.1. In addition, by using the overall suppression factor 0.5, H1 obtained a good description of all the measured distributions in the variables $z_{I\!P}^{obs}$, x_γ^{obs}, $x_{I\!P}$, W, E_T^{jet1}, $\bar{\eta}_{jet}^{lab}$, $|\Delta\eta_{jet}|$ and M_{12} interfaced with the 'H1 2006 fit B' DPDFs and taking into account hadronization corrections [28]. Finally, the H1 collaboration investigated how well the data are describable under the assumption that in the NLO calculation the cross section for $x_\gamma^{obs} > 0.9$ is not suppressed. The best agreement in a fit was obtained for a suppression factor 0.44 for the NLO calculation with $x_\gamma^{obs} < 0.9$, based on fitting the distributions for $x_\gamma^{obs}, W, \bar{\eta}_{jet}^{lab}$ and E_T^{jet1}. In this comparison they found disagreement for the largest x_γ^{obs}-bin and the lowest $\bar{\eta}_{jet}^{lab}$-bin (which are related),

but better agreement in the E_T^{jet1}-distribution. In [28] this leads to the statement, that the assumption that the direct cross section obeys factorization is strongly disfavored by their analysis. In total, it is obvious that in the final H1 analysis [28] a global suppression in diffractive dijet photoproduction is clearly established.

Just recently also the ZEUS collaboration presented their final result on diffractive dijet photoproduction [29]. As in their preliminary analysis, the two jets with the highest transverse energies E_T^{jet} were required to satisfy $E_T^{jet1(2)} > 7.5$ (6.5) GeV, which is higher than in the H1 analysis with $E_T^{jet1(2)} > 5$ (4) GeV [28]. ZEUS compared their measurements with the NLO predictions for diffractive photoproduction of dijets based on our program [19]. Three sets of DPDFs were used, the ZEUS LPS fit, determined from a NLO analysis of inclusive diffraction and diffractive charm-production data [3], and the two H1 fits, 'H1 2006 fits A,B' [4]. The NLO results obtained with the two H1 fits were scaled down by a factor of 0.87 [4] since the H1 measurements used to derive the DPDFs include low-mass proton dissociative processes with $M_Y < 1.6$ GeV, which increases the photon-diffractive cross section by $1.15^{+0.15}_{-0.08}$ as compared to the pure proton final state as corrected to in the ZEUS analysis. The comparison of the measured cross sections and the theoretical predictions was based on the differential cross sections in the variables y, M_X, $x_{I\!P}$, $z_{I\!P}^{obs}$, E_T^{jet1}, η^{jet1} and x_γ^{obs}. The data were reasonably well described in their shape as a function of these variables and lay systematically below the predictions. The predictions for the three DPDFs differed appreciably. The cross sections for the 'H1 2006 fit A' ('H1 2006 fit B') were the highest (lowest), and the one for the ZEUS LPS fit lay between the two, but nearer to the fit A than the fit B predictions. For $d\sigma/dx_\gamma^{obs}$ ZEUS also showed the ratio of the data and the NLO predictions using the ZEUS LPS fit. The ratio was consistent with a suppression factor of 0.7 independent of x_γ^{obs}. This suppression factor depended on the DPDFs and ranged between 0.6 ('H1 2006 fit A') and 0.9 ('H1 2006 fit B'). Taking into account the scale dependence of the theoretical predictions the ratio was outside the theoretical uncertainty for the ZEUS LPS fit and the 'H1 2006 fit A', but not for the 'H1 2006 fit B'. In their conclusions the authors of the ZEUS analysis [29] made the statement that the NLO calculations tend to overestimate the measured cross section, which would mean that a suppression is present. Unfortunately, however, they continued, that, within the large uncertainties of the NLO calculations, the data were compatible with the QCD calculations, i.e. with no suppression.

Such a statement clearly contradicts the result of the H1 collaboration [28] and casts

doubts on the correctness of the H1 analysis. The authors of [29] attribute this discrepancy to the fact that the H1 measurements [28] were carried out in a lower E_T^{jet} and a higher $x_{I\!P}$ range than those in the ZEUS study [29]. Besides the different E_T^{jet} and $x_{I\!P}$ regions in [28] and [29] the two measurements suffer also from different experimental cuts of some other variables which makes it difficult to compare the two data sets directly (note also the lower center-of-mass energy for the H1 data). With this in mind the H1 collaboration has done a second analysis [30, 31], in which most of the experimental cuts are taken as in the ZEUS [29] analysis, i.e. the cuts on $x_{I\!P}$, $\eta^{jet1(2)}$ and on $E_T^{jet1(2)}$. In addition they analyzed data sets also with the lower E_T^{jet} cut, namely $E_T^{jet1(2)} > 5$ (4) GeV and with $x_{I\!P} < 0.03$ as in the previous H1 dijet analysis [28]. Starting from these recent data [30, 31] we have performed a new calculation of the NLO cross sections on the basis of [19] for the new H1 [30, 31] and the latest ZEUS [29] analyses with the same DPDFs as input, in order to see whether we can confirm the different conclusions obtained from the older H1 [28] and the ZEUS [29] measurements. In this new comparison between the experimental and the theoretical results we shall concentrate on using the 'H1 2006 fit B' as DPDF input, since it leads to smaller NLO cross sections than the DPDFs based on the 'H1 2006 fit A' or the ZEUS LPS fit.

In section 2 we shall present, after defining the complete list of cuts on the experimental variables and giving all the input used in the cross section calculations, the comparison with the new H1 experimental data [30, 31]. In this comparison we shall concentrate on the main question, whether there is a suppression in the photoproduction data at all. In addition we shall investigate also whether a reasonable description of the data is possible with suppression of the resolved cross section only, as we studied it already in our previous work in 2004 [18, 19]. In section 3 the same comparison with the ZEUS data [29] will be performed. In section 4 we shall finish with a summary and our conclusions.

II. COMPARISON WITH RECENT H1 DATA

The recent H1 data for diffractive photoproduction of dijets [30, 31] have several advantages as compared to the earlier H1 [28] and ZEUS [29] analyses. First, the integrated luminosity is three times higher than in the previous H1 analysis [28] comparable to the luminosity in the ZEUS analysis [29]. Second, H1 took data with low-E_T^{jet} [30, 31] and high-E_T^{jet} [31] cuts, which allows the comparison with [28] and [29]. The exact two kine-

TABLE I: Kinematic cuts applied in the most recent H1 analyses of diffractive dijet photoproduction [30, 31].

H1 low-E_T^{jet} cuts	H1 high-E_T^{jet} cuts
$Q^2 < 0.01$ GeV^2	$Q^2 < 0.01$ GeV^2
$0.3 < y < 0.65$	$0.3 < y < 0.65$
$E_T^{jet1} > 5$ GeV	$E_T^{jet1} > 7.5$ GeV
$E_T^{jet2} > 4$ GeV	$E_T^{jet2} > 6.5$ GeV
$-1 < \eta^{jet1(2)} < 2$	$-1.5 < \eta^{jet1(2)} < 1.5$
$z_{I\!P} < 0.8$	$z_{I\!P} < 1$
$x_{I\!P} < 0.03$	$x_{I\!P} < 0.025$
$\|t\| < 1$ GeV^2	$\|t\| < 1$ GeV^2
$M_Y < 1.6$ GeV	$M_Y < 1.6$ GeV

matic ranges are given in Tab. 1. These ranges for the low-E_T^{jet} cuts are as in the previous H1 analysis [28] and for the high-E_T^{jet} cuts are chosen as in the ZEUS analysis with two exceptions. In the ZEUS analysis the maximal cut on Q^2 is larger and the data are taken in an extended y range. The definition of the various variables can be found in the H1 and ZEUS publications [28, 29] and in our previous work [18, 19]. Very important is the cut on $x_{I\!P}$. It is kept small in both analysis in order for the pomeron exchange to be dominant. We base our analysis on the low-E_T data published in [30], which differ from the data in [31] in the cut on $z_{I\!P}$ influencing not only the experimental data, but also the NLO results in all variables except the distribution in $z_{I\!P}$. The preliminary low-E_T^{jet} data [31] have been compared previously to our theoretical results at NLO in [32]. In the experimental analysis as well as in the NLO calculations, jets are defined with the inclusive k_T-cluster algorithm with a distance parameter $d = 1$ [33] in the laboratory frame. At least two jets are required with the respective cuts on E_T^{jet1} and E_T^{jet2}, where $E_T^{jet1(2)}$ refers to the jet with the largest (second largest) E_T^{jet}. As is well known, the lower limits on the jet E_T are chosen asymmetric in order to avoid an infrared sensitivity in those NLO cross section computations, which are integrated over E_T^{jet} [34].

Before we confront the calculated cross sections with the experimental data, we correct them for hadronization effects. The hadronization corrections are calculated by means of the

LO RAPGAP Monte Carlo generator [15]. The factors for the transformation of jets made up of stable hadrons to parton jets were supplied by the H1 collaboration [30, 31]. Most of our calculations are done with the 'H1 2006 fit B' [4] DPDFs, since they give the smaller diffractive dijet cross sections as compared to the 'H1 2006 fit A'. The H1 and ZEUS collaborations constructed two more sets of DPDFs, which are called 'H1 2007 fit jets' and 'ZEUS DPDF SJ'. These fits are obtained through simultaneous fits to the diffractive inclusive and DIS dijet cross sections [35]. In these fits it is assumed that there is no factorization breaking in the diffractive DIS dijet cross sections. Including these cross sections in the fits leads to additional constraints, mostly for the diffractive gluon distribution. On average the 'H1 2007 fit jets' is similar to the 'H1 2006 fit B' except for the gluon distribution at large momentum fraction and small factorization scale. In the following analysis we shall disregard these new DPDF sets, since they would be compatible with the factorization test of the photoproduction data only, if we restricted these tests to the case that the resolved part has the breaking and not the direct part, which has the same theoretical structure as the DIS dijet cross section. Results with the 'H1 2007 fit jets' can be found in [30, 31]. The 'H1 2006 fits A,B' are based on $n_f = 3$ massless flavors. The production of charm quarks was treated in the Fixed-Flavor Number Scheme (FFNS) in NLO with non-zero charm-quark mass yielding a diffractive F_2^c. This F_2^c is contained in the 'H1 2006 fits A,B' parameterizations and is then converted by us into a charm PDF using the LO expression $F_2^c(x,Q^2) = 2xe_c^2 f_c(x,Q^2)$, where $e_c = 2/3$ is the electric charge of the charm quark. The bottom contribution was neglected. This assumption simplifies the calculations considerably. Since the charm contribution from the Pomeron is small, this should be a good approximation. We then take $n_f = 4$ with $\Lambda^{(4)}_{\overline{\rm MS}} = 0.347$ GeV, which corresponds to the value used in the DPDFs 'H1 2006 fits A,B' [4]. For the photon PDF we have chosen the NLO GRV parametrization transformed to the $\overline{\rm MS}$ scheme [36].

As it is clear from the discussion of the various preliminary analyses of the H1 and ZEUS collaborations, there are two questions which we would like to answer from the comparison with the recent H1 and the ZEUS data. The first question is whether a suppression factor (sometimes also called rapidity-gap survival probability), which differs substantially from one, is needed to describe the data. The second question is whether the data are also consistent with a suppression factor applied to the resolved cross section only. To give an answer to these two questions we calculated first the cross sections with no suppression

factor ($R = 1$ in the following figures) with a theoretical error obtained from varying the common scale of renormalization and factorization by factors of 0.5 and 2 around the default value (highest E_T^{jet}). In a second step we show the results for the same differential cross sections with a global suppression factor, adjusted to $d\sigma/dE_T^{jet1}$ at the smallest E_T^{jet1}-bin. As in the experimental analyses [30, 31], we consider the differential cross sections in the variables x_γ^{obs}, $z_{I\!P}^{obs}$, $\log_{10}(x_{I\!P})$, E_T^{jet1}, M_X, M_{12}, $\overline{\eta}^{jets}$, $|\Delta\eta^{jets}|$ and W. The definition of the variables is given in the experimental papers [28–31] or in our earlier work [18, 19, 37]. In the latter references also the relevant formulas for the calculation of the dijet cross sections can be found.

For the low-E_T^{jet} cuts, the resulting suppression factor is $R = 0.50 \pm 0.09$, which gives in the lowest E_T^{jet1}-bin a cross section equal to the experimental data point. The error comes from the combined experimental statistical and systematic error. The theoretical error due to the scale variation is taken into account when comparing to the various distributions. The result of this comparison is shown in Figs. 3a-i. With the exception of Figs. 3d and 3f, where the comparisons of $d\sigma/dE_T^{jet1}$ and $d\sigma/dM_{12}$ are shown, all other plots are such that the data points lie outside the error band based on the scale variation for the unsuppressed case. However, the predictions with suppression $R = 0.50$ agree nicely with the data inside the error bands from the scale variation. Most of the data points even agree with the $R = 0.50$ predictions inside the much smaller experimental errors. The M_X-distribution agrees only for the second bin. The reason for the disagreement of the two other M_X-bins might be that in the theoretical results the variable M_X is defined without the remnant contributions, which, however, are taken into account in the experimental definition of M_X. Further exceptions are the cross sections $d\sigma/dE_T^{jet1}$ and dσ/dM_{12}, which are related. In $d\sigma/dE_T^{jet1}$ (see Fig. 3d) the predictions for the second and third bins lie practically outside the data points with their errors (note the logarithmic scale). For $R = 1$ and $R = 0.50$ the cross sections fall off stronger with increasing E_T^{jet1} than the data, the normalization being of course about two times larger for $R = 1$. In particular, the third data point agrees almost with the $R = 1$ prediction. This means that the suppression decreases with increasing E_T^{jet1}. This behavior was already apparent when we analyzed the first preliminary H1 data [18, 19]. Such a behavior points in the direction that a suppression of the resolved cross section only would give better agreement with the data, as we shall see below. The same observations can be made by looking at $d\sigma/dM_{12}$ in Fig. 3f. The survival probability $R = 0.50 \pm 0.09$ agrees

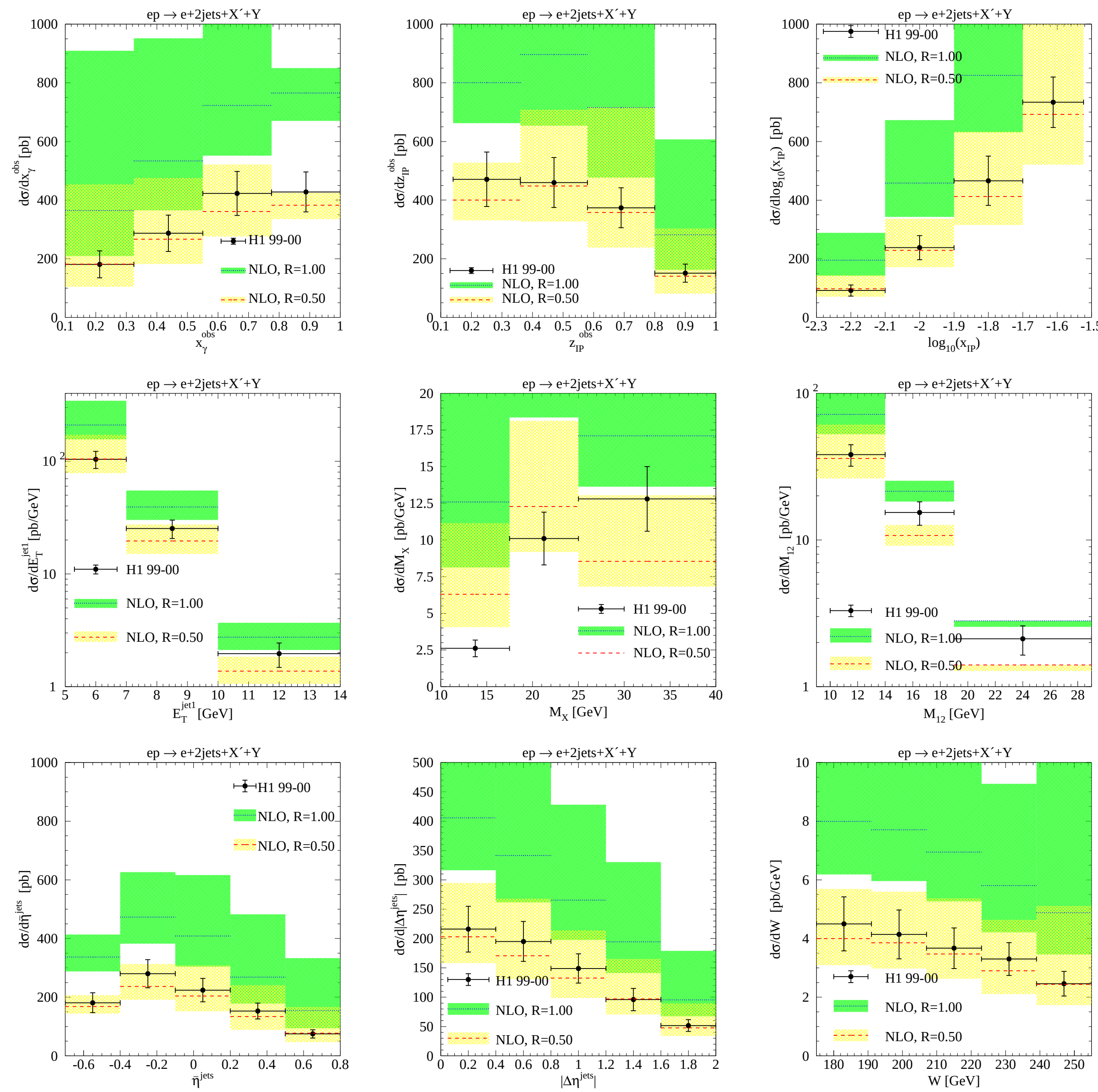

FIG. 3: Differential cross sections for diffractive dijet photoproduction as measured by H1 with low-E_T^{jet} cuts and compared to NLO QCD without ($R = 1$) and with ($R = 0.50$) global suppression (color online).

with the result in [30], which quotes $R = 0.58 \pm 0.01$ (stat.) $\pm\ 0.12$ (syst.), determined by fitting the integrated cross section. From our comparison we conclude that the low-E_T^{jet} data show a global suppression of the order of two in complete agreement with the results in [18, 19] and [28] based on earlier preliminary [14] and final H1 data [28].

Next we want to answer the second question, whether the data could be consistent with

a suppression of the resolved component only, whose definition is not unique, but rather factorization scale and scheme dependent. For this purpose we have calculated the cross sections in two additional versions: (i) suppression of the resolved cross section in the $\overline{\text{MS}}$ scheme and (ii) suppression of this resolved cross section plus that part of the NLO direct part which depends on the factorization scale at the photon vertex [38]. Of course, the needed suppression factors for the two versions will be different. We determine the suppression factors again by fitting the measured $d\sigma/dE_T^{jet1}$ for the lowest E_T^{jet1}-bin (see Fig. 4d). Then, the suppression factor for version (i) is $R = 0.40$ (denoted res in the figures), and for version (ii) it is $R = 0.37$ (denoted res+dir-IS). The comparison with the H1 data of $d\sigma/dx_\gamma^{obs}$, $d\sigma/dz_{I\!P}^{obs}$, $d\sigma/d\log_{10}(x_{I\!P})$, $d\sigma/dE_T^{jet1}$, $d\sigma/dM_X$, $d\sigma/dM_{12}$, $d\sigma/d\bar{\eta}^{jets}$, $d\sigma/d|\Delta\eta^{jets}|$ and $d\sigma/dW$ is shown in Figs. 4a-i, where we have also plotted the prediction for the global suppression (direct and resolved) with $R = 0.50$, already shown in Figs. 3a-i. Looking at the Figs. 4a-i we can distinguish three groups of results from the comparison with the data. In the first group, the cross sections as functions of $z_{I\!P}^{obs}$, $log_{10}(x_{I\!P})$, M_{12}, $\bar{\eta}^{jets}$, $|\Delta\eta|^{jets}$ and W, the agreement with the global suppression ($R = 0.50$) and the resolved suppression ($R = 0.40$ or $R = 0.37$) is comparable. In the second group, namely for $d\sigma/dE_T^{jet1}$, the agreement is better for the resolved suppression only. In the third group, $d\sigma/dx_\gamma^{obs}$ and $d\sigma/dM_X$, the agreement with the resolved suppression is worse than with the global suppression. In particular, for $d\sigma/dx_\gamma^{obs}$, which is usually considered as the characteristic distribution for distinguishing global versus resolved suppression, the agreement with resolved suppression does not improve. Unfortunately, this cross section has the largest hadronic corrections of the order of $(20-30)\%$ [30]. Second, also for the usual photoproduction of dijets the comparison between data and theoretical results has similar problems in the large x_γ^{obs}-bin [39], although the E_T^{jet} cut is much larger there. On the other hand, for the cross sections $d\sigma/dE_T^{jet1}$ (and $d\sigma/dM_{12}$) the agreement improves considerably (and somewhat) with the suppression of the resolved part only (note the logarithmic scale in Fig. 4d). Here, of course, we must admit that the suppression factor could be E_T-dependent, although we see no theoretical reason for such a dependence.

We also checked for two distributions whether the predictions for resolved suppression depend on the chosen diffractive PDFs. For this purpose we have calculated for the two cases $d\sigma/dz_{I\!P}^{obs}$ and $d\sigma/dE_T^{jet1}$ the cross sections with the 'H1 2006 fit A' parton distributions [4]. The results are compared in Figs. 5a and b to the results with the 'H1 2006 fit B' and the

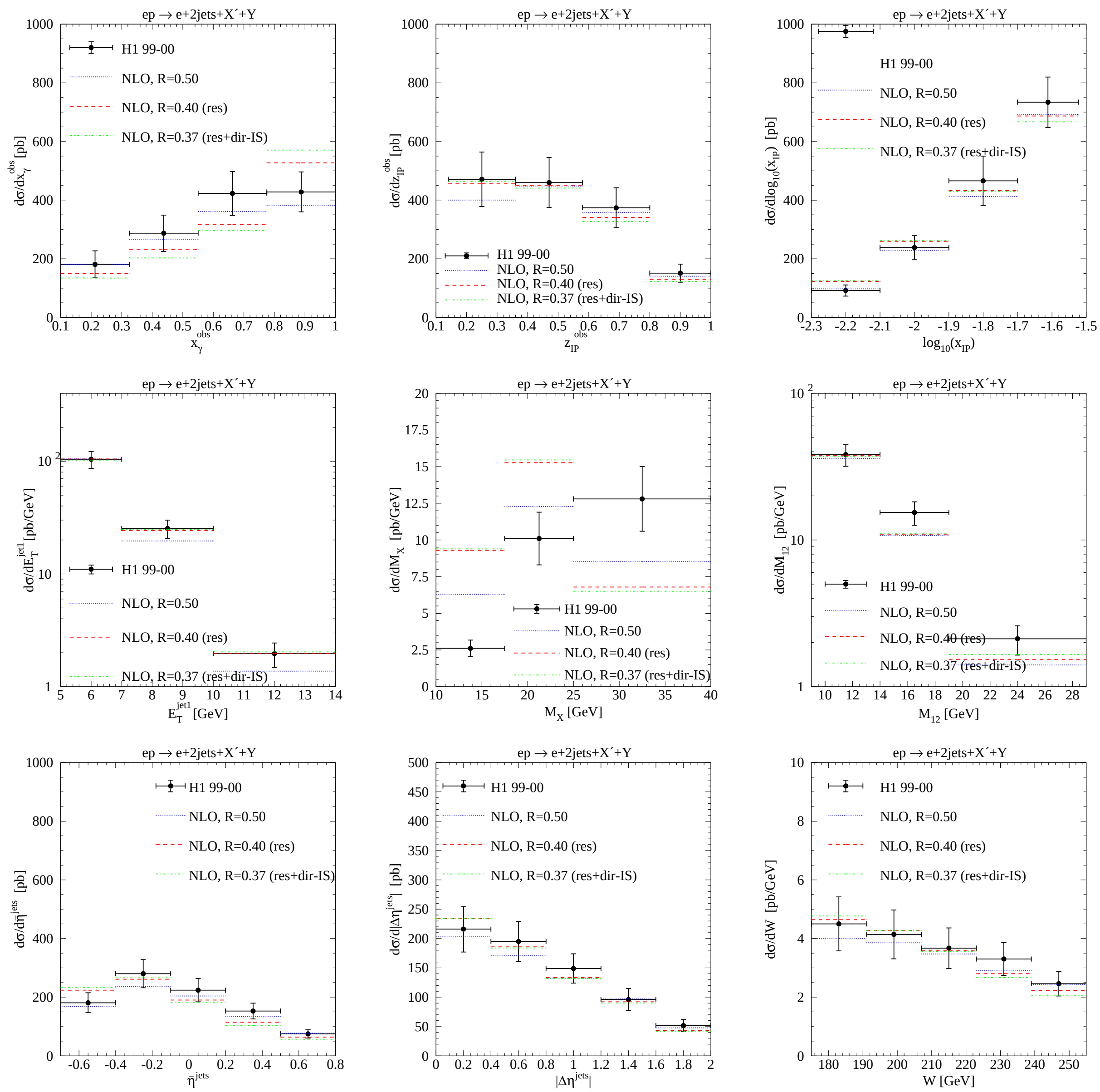

FIG. 4: Differential cross sections for diffractive dijet photoproduction as measured by H1 with low-E_T^{jet} cuts and compared to NLO QCD with global, resolved, and resolved/direct-IS suppression. Note that some of the theoretical predictions coincide with the experimental values.

experimental data. Of course, since the 'H1 2006 fit A' PDFs have a larger gluon component at large z, the cross sections are larger and therefore need a larger suppression of $R = 0.32$. Note that in the published low-E_T^{jet} H1 analysis as well as in the comparison presented here the contribution from the largest $z_{I\!P}^{obs}$-bin has been removed from all other distributions. From Figs. 5a and b we conclude that the dependence on the chosen DPDFs is then weaker,

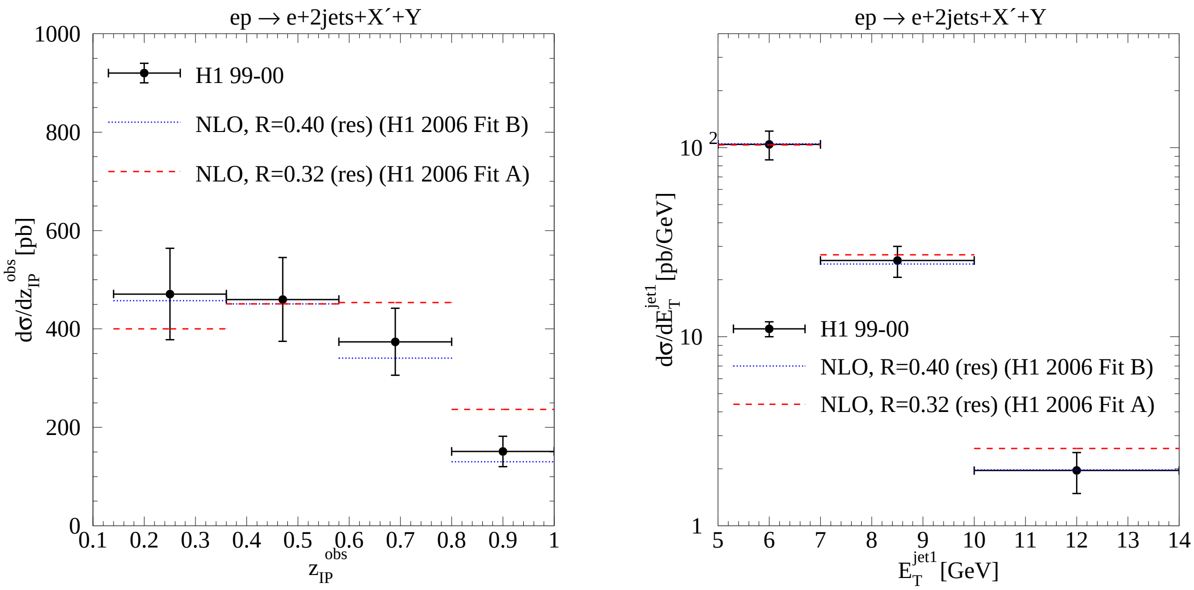

FIG. 5: Differential cross sections for diffractive dijet photoproduction as measured by H1 with low-E_T^{jet} cuts and compared to NLO QCD with resolved suppression and two different DPDFs.

but that 'H1 2006 fit B' is still favored over 'H1 2006 fit A'. In total, we are tempted to conclude from the comparisons in Figs. 4a-i that the predictions with a resolved-only (or resolved+direct-IS) suppression are consistent with the new low-E_T^{jet} H1 data [30].

The same comparison of the high-E_T^{jet} data of H1 [31] with the various theoretical predictions is shown in the following figures. The global suppression factor is obtained again from a fit to the smallest E_T^{jet1}-bin. It is equal to $R = 0.62 \pm 0.16$, again in agreement with the H1 result $R = 0.62 \pm 0.03$ (stat.) ± 0.14 (syst.) [31] obtained with our theoretical cross sections. The comparisons of the same cross sections as in the low-E_T^{jet} comparison are shown in Figs. 6a-i for the two cases $R = 1$ (no suppression) and $R = 0.62$ (global suppression). As before with the exception of $d\sigma/dE_T^{jet1}$ and $d\sigma/dM_{12}$ in Fig. 6d and Fig. 6f, most of the data points lie outside the $R = 1$ results with their error bands and agree with the suppressed prediction with $R = 0.62$ inside the respective errors. However, compared to the results in Figs. 3a-i the distinction between the $R = 1$ band and the $R = 0.62$ band and the data is somewhat less pronounced. We also tested the prediction for the resolved (resolved+direct-IS) suppression, which is shown in Figs. 7a-i. The suppression factor fitted to the smallest E_T^{jet1}-bin came out as $R = 0.38$ (res) and $R = 0.30$ (res+dir-IS). In most of the comparisons it is hard to observe any preference for the direct plus resolved (global)

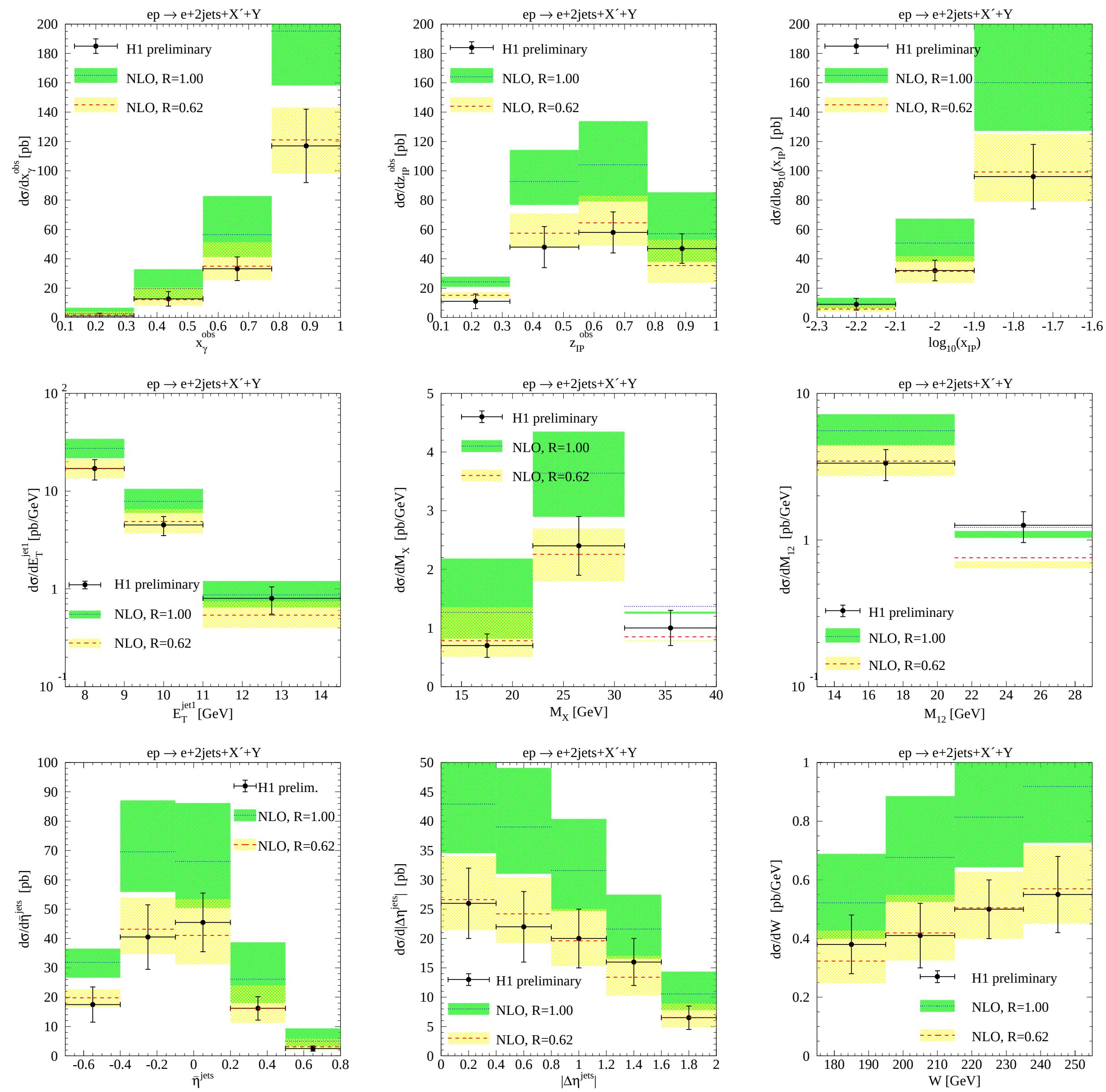

FIG. 6: Differential cross sections for diffractive dijet photoproduction as measured by H1 with high-E_T^{jet} cuts and compared to NLO QCD without ($R = 1$) and with ($R = 0.62$) global suppression (color online).

suppression against the resolved suppression only. We remark that the suppression factor for the global suppression is increased by 24%, if we go from the low-E_T^{jet} to the high-E_T^{jet} data, whereas for the resolved suppression the difference is only 5%. Under the assumption that the suppression factor should not depend on E_T^{jet1}, we would conclude that the version with the resolved suppression would be preferred. In Figs. 8a and b we tested the resolved

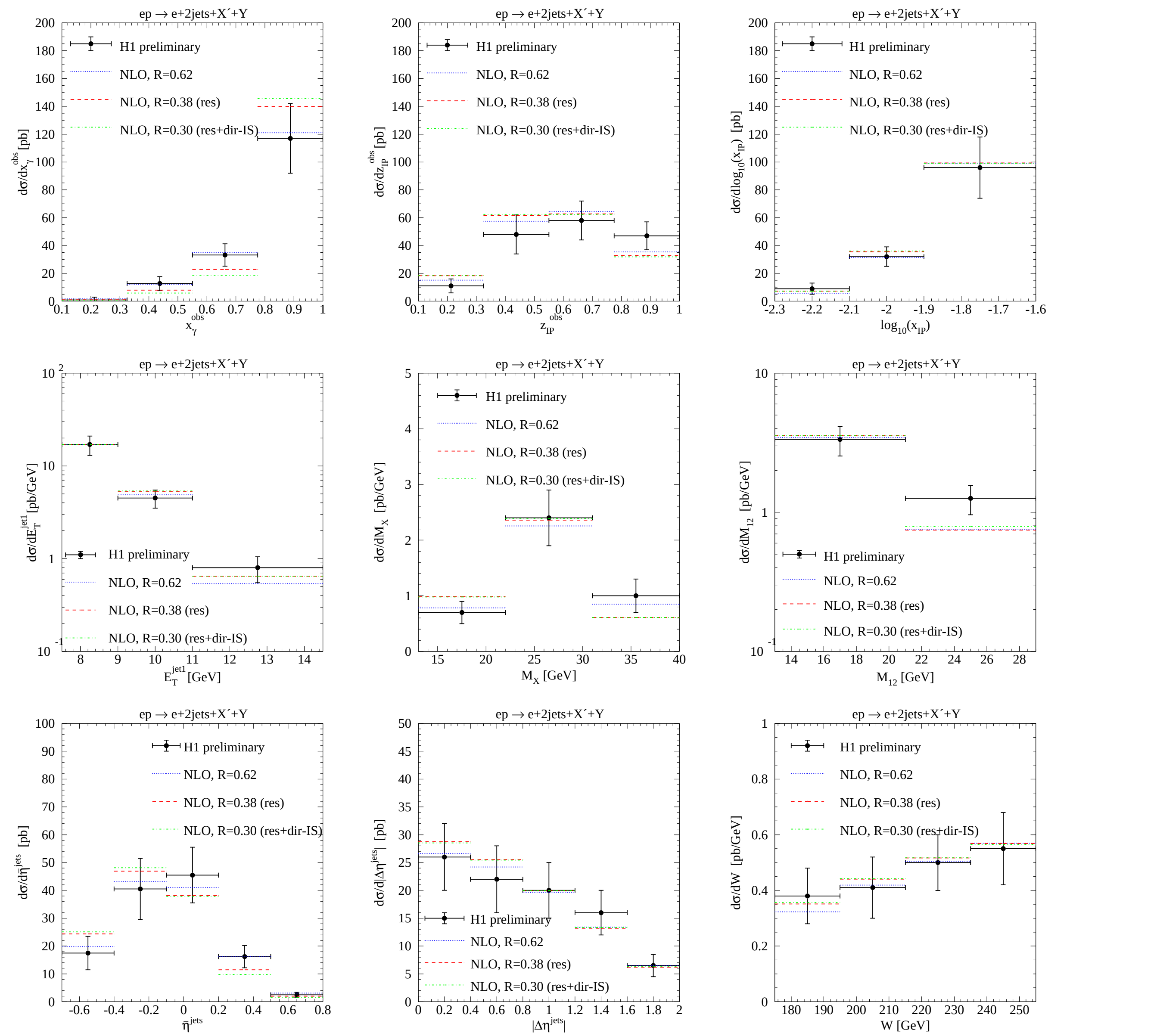

FIG. 7: Differential cross sections for diffractive dijet photoproduction as measured by H1 with high-E_T^{jet} cuts and compared to NLO QCD with global, resolved, and resolved/direct-IS suppression.

suppression model against the choice of the two DPDFs, fit A versus fit B, with the result that this dependence is weak if we adjust the suppression factor, which is $R = 0.16$ for the 'H1 2006 fit A'. The general conclusions from the high-E_T^{jet} comparison are very much the same as from the low-E_T^{jet} comparison. A global suppression is definitely observed and the version with resolved suppression explains the data almost as well as with the global

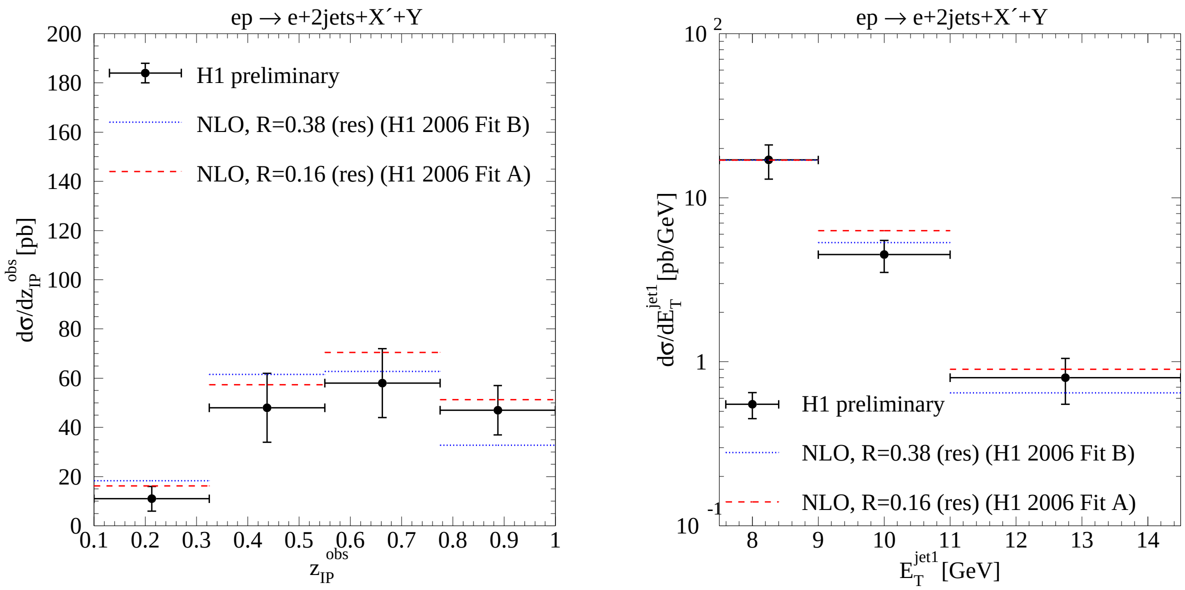

FIG. 8: Differential cross sections for diffractive dijet photoproduction as measured by H1 with high-E_T^{jet} cuts and compared to NLO QCD with resolved suppression and two different DPDFs.

suppression.

III. COMPARISON WITH ZEUS DATA

In this section we shall compare our predictions with the final analysis of the ZEUS data, which was published just recently [29], in order to see whether they are consistent with the large-E_T^{jet} data of H1. The kinematic cuts are almost the same as in the high-E_T^{jet} H1 measurements. They are given in Tab. 2. The only major difference to the H1 cuts in Tab. 1 is the larger range in the variable y. Therefore the ZEUS cross sections will be larger than the corresponding H1 cross sections. The different cuts on Q^2 and $|t|$ have little influence. For example, the larger $|t|$-cut in Tab. 2 as compared to Tab. 1 increases the cross section only by 0.2%. The constraint on M_Y is not explicitly given in the ZEUS publication [29]. They give the cross section for the case that the diffractive final state consists only of the proton. For this they correct their measured cross section by subtracting in all bins the estimated contribution of a proton-dissociative background of 16%. When comparing to the theoretical predictions they do the reverse and multiply the cross section with the factor 0.87, in order to correct for the proton-dissociative contributions, which are contained in the

TABLE II: Kinematic cuts applied in the most recent ZEUS analysis of diffractive dijet photoproduction [29].

ZEUS cuts
$Q^2 < 1$ GeV^2
$0.2 < y < 0.85$
$E_T^{jet1} > 7.5$ GeV
$E_T^{jet2} > 6.5$ GeV
$-1.5 < \eta^{jet1(2)} < 1.5$
$x_{I\!P} < 0.025$
$\|t\| < 5$ GeV^2

DPDFs 'H1 2006 fit A' and 'H1 2006 fit B' by requiring $M_Y < 1.6$ GeV. We do not follow this procedure. Instead we leave the theoretical cross sections unchanged, i.e. they contain a proton-dissociative contribution with $M_Y < 1.6$ GeV, and multiply the ZEUS cross sections by 1.15 to include the proton-dissociative contribution. Since the ZEUS collaboration did measurements only for the high-E_T^{jet} cuts, $E_T^{jet1(2)} > 7.5$ (6.5) GeV, we can only compare to those. In this comparison we shall follow the same strategy as before. We first compare to the predictions with no suppression ($R = 1$) and then determine a suppression factor by fitting $d\sigma/dE_T^{jet1}$ to the smallest E_T^{jet1}-bin. Then we compare to the cross sections as a function of the seven observables x_γ^{obs}, $z_{I\!P}^{obs}$, $x_{I\!P}$, E_T^{jet1}, y, M_X and η^{jet1} instead of the nine variables in the H1 analysis. The distribution in y is equivalent to the W-distribution in [31]. The theoretical predictions for these differential cross sections with no suppression factor ($R = 1$) are shown in Figs. 9a-g, together with their scale errors and compared to the ZEUS data points. Except for the x_γ^{obs}- and E_T^{jet1}-distributions, most of the data points lie outside the theoretical error bands for $R = 1$. In particular, in Figs. 9b, c, e, f and g, 2, 3, 4, 4 and 5 points lie outside. This means that most of the data points disagree with the unsuppressed prediction. Next, we determine the suppression factor from the measured $d\sigma/dE_T^{jet1}$ at the lowest E_T^{jet1}-bin, 7.5 GeV $< E_T^{jet1} <$ 9.5 GeV, and obtain $R = 0.71$. As a curiosity, we remark that this factor is larger by a factor of 1.15 than the suppression factor from the analysis of the high-E_T^{jet} data from H1. This factor is exactly equal to the correction factor we had to apply to restore the dissociative proton contribution. Without

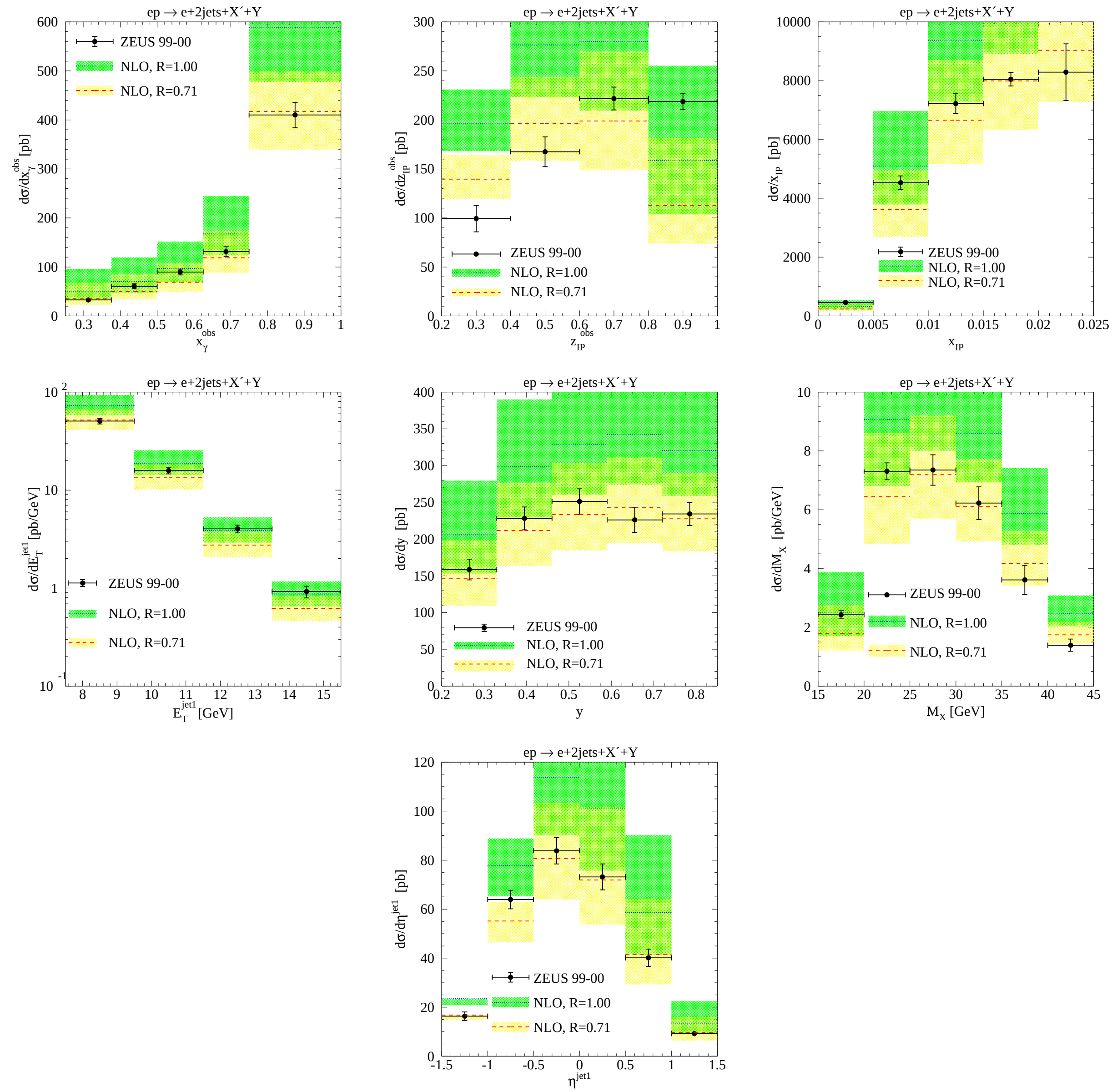

FIG. 9: Differential cross sections for diffractive dijet photoproduction as measured by ZEUS and compared to NLO QCD without ($R = 1$) and with ($R = 0.71$) global suppression (color online).

this correction factor the suppression factor following from the ZEUS analysis would be in perfect agreement with the factor in the H1 analysis. Taking the total experimental error of $\pm 7\%$ from the experimental cross section $d\sigma/dE_T^{jet1}$ in the first bin into account, the ZEUS suppression factor is 0.71 ± 0.05 to be compared to 0.62 ± 0.14 in the H1 analysis [31], so that both suppression factors agree inside the experimental errors.

If we now check how the predictions for $R = 0.71$ compare to the data points inside

the theoretical errors, we observe from Figs. 9a-g that with the exception of $d\sigma/dz_{I\!P}^{obs}$ and $d\sigma/dE_T^{jet1}$ the majority of the data points agree with the predictions. This is quite consistent with the H1 analysis, discussed in the previous section, and leads to the conclusion that also the ZEUS data agree much better with the suppressed predictions than with the unsuppressed prediction. In particular, the global suppression factor agrees with the global suppression factor obtained from the analysis of the H1 data inside the experimental error.

Similarly as in the previous section we compared the ZEUS data also with the assumption that the suppression results only from the resolved cross section. Here we consider again the two versions: (i) only resolved suppression (res) and (ii) resolved plus direct suppression of the initial-state singular part (res+dir-IS). For these two models we obtain the suppression factors $R = 0.53$ and $R = 0.45$, respectively, where these suppression factors are again obtained by fitting the data point at the first bin of $d\sigma/dE_T^{jet1}$. The comparison to the global suppression with $R = 0.71$ and to the data is shown in Figs. 10a-g. In general, we observe that the difference between global suppression and resolved suppression is small, i.e. the data points agree with the resolved suppression as well as with the global suppression.

In Figs. 11a and b the difference between 'H1 2006 fit B' and 'H1 2006 fit A' is shown again for the case of the resolved suppression. In both figures we observe that the fit A suppression with the suppression factor $R = 0.27$ agrees better with the data than with the factor $R = 0.53$ for the fit B suppression. In particular, for $d\sigma/dE_T^{jet1}$ the agreement with the three data points is perfect (note the logarithmic scale).

In our analysis of the ZEUS data so far we assumed that the measurements with the large rapidity gap (LRG) method of ZEUS in [29] are such that with this method the same inclusive diffractive DIS cross section is measured as in in the H1 measurement of this cross section with the LRG method [4], on which the fits of the DPDFs 'H1 2006 fits A,B' are based. This is actually not true, and this problem has been analysed by the ZEUS collaboration in their publication, in which they present their data for the inclusive diffractive DIS cross sections using different definitions for these cross sections [40]. They find that their LRG cross section has to be corrected by two factors in order to make it agree with the H1 measurement of the diffractive DIS cross section and with the prediction of this cross section based on the 'H1 2006 fit B'. First, a factor of 0.91 ± 0.07 was estimated with the PYTHIA Monte Carlo, so that the ZEUS cross sections correspond to a dissociative background with $M_Y < 1.6$ GeV. Second, even then the so corrected ZEUS diffractive DIS cross section was still 13%

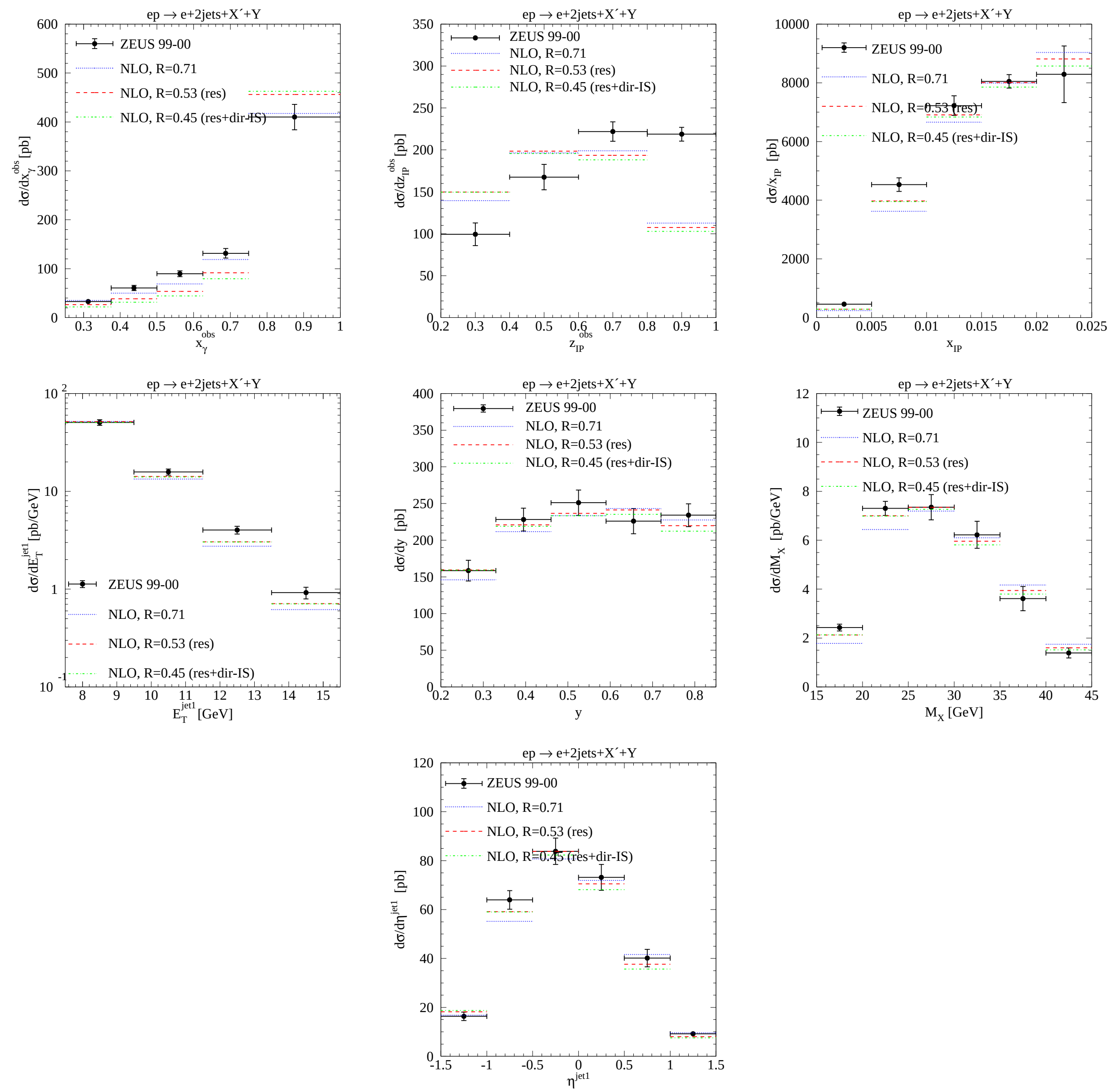

FIG. 10: Differential cross sections for diffractive dijet photoproduction as measured by ZEUS and compared to NLO QCD with global, resolved, and resolved/direct-IS suppression.

larger than the corresponding H1 diffractive DIS cross section. This amounts to a total correction factor of 0.79 ± 0.06. If we apply this correction factor to our ZEUS suppression factors, we obtain a global (resolved-only) suppression of 0.56 ± 0.05 rather than 0.71 (0.42 $\pm$ 0.04 rather than 0.53), i.e. suppression factors which are closer to the results found for the similar high-E_T^{jet} H1 analysis. Here, the errors refer only to the errors coming from the renormalization of the ZEUS data and do not include the experimental stat./syst. and

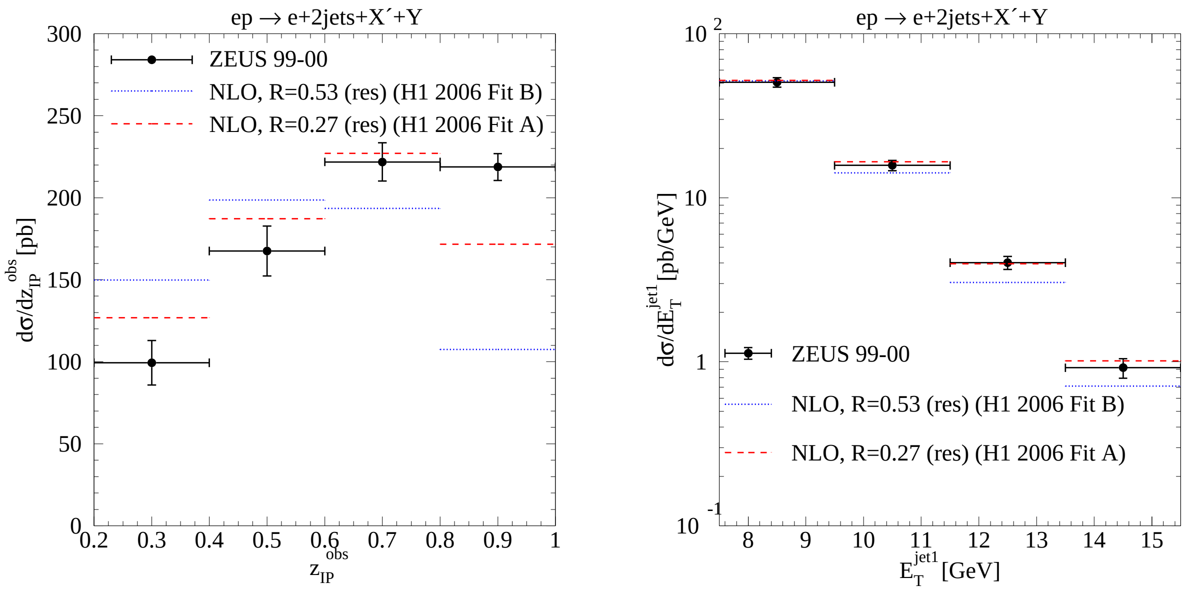

FIG. 11: Differential cross sections for diffractive dijet photoproduction as measured by ZEUS and compared to NLO QCD with resolved suppression and two different DPDFs.

theoretical scale errors.

IV. CONCLUSION

In this paper, we confronted the final HERA data on the diffractive photoproduction of dijets, as published by the ZEUS [29] and H1 [30, 31] collaborations, with our NLO QCD calculations in order to see if factorization breaking effects in the resolved and eventually direct cross sections can be established consistently from both data sets. The new comparison is even more conclusive than the one published previously in our invited review [37], as the proton beam energy of 920 GeV, the cuts on the jet transverse energies of $E_T^{jet1(2)} > 7.5$ (6.5) GeV, and the cut on the momentum fraction carried by the diffractive exchange $x_{I\!P} < 0.025$ are now the same in both experiments, which was not the case before. At the same time, some experimental cuts are still different. In particular, the momentum fraction y transferred by the electron to the hadronic system is larger for ZEUS than for H1. We also re-computed in NLO QCD the cross sections for the lower cuts on $E_T^{jet1(2)} > 5$ (4) GeV, which have been re-measured by the H1 collaboration [30, 31] in order to establish consistency with the their previous low-luminosity data set [28]. We found that the large majority of H1 and

TABLE III: Suppression factors for global and resolved-only suppression in the low-E_T^{jet} and high-E_T^{jet} analyses of H1 and the ZEUS analysis before and after rescaling their data by a factor of 1.15.

Suppression factor	H1 low-E_T^{jet}	H1 high-E_T^{jet}	ZEUS	ZEUS renormalized
global	0.50	0.62	0.71	0.56 ± 0.05
resolved-only	0.40	0.38	0.53	0.42 ± 0.04
res+dir-IS	0.37	0.30	0.45	0.36 ± 0.03
res, H1 2006 fit A	0.32	0.16	0.27	0.21 ± 0.01

ZEUS data points lay below the NLO QCD predictions, even when using the 'H1 2006 fit B' diffractive PDFs with small gluon density at large fractional momentum and taking into account the experimental (statistical and systematic) and theoretical (scale variation) errors. The data at larger E_T^{jet1} (or M_{12}) tended to agree better with the NLO QCD predictions than those at small E_T^{jet1}.

By fitting the lowest (and dominant) bins in the three E_T^{jet1}-distributions, we established the amounts by which *both* the direct and resolved NLO QCD cross sections had to be reduced to find agreement with the data. These suppression factors are shown in the second line ('global') of Tab. 3 for the low-E_T^{jet} and high-E_T^{jet} analyses of H1, the ZEUS analysis (multiplied by a factor of 1.15 to allow for proton dissociation), and the ZEUS analysis renormalized by a factor of 0.79 ± 0.06 for $M_Y < 1.6$ GeV and correspondance with the H1 measurements and DPDF fits [40]. The first, second and third factors agreed very well with those found by the experimental collaborations when fitting multiple distributions or total cross sections. The fourth factor ('ZEUS renormalized') agrees better with the second factor, relevant for the similar high-E_T^{jet} H1 analysis. We also tested the hypotheses that factorization breaking is only present in the resolved (third line) or the resolved and the related initial-state singular part of the direct photoproduction cross sections (fourth line). Both hypotheses gave very similar results and described the data sets almost as well as the predictions with global factorization breaking. The suppression factors applicable to just the resolved cross section are shown in the third line of Tab. 3. As observed previously [19], they agree very well with absorptive-model predictions [13]. We conclude that in this case the suppression factors do not show a significant E_T^{jet}-dependence, in particular when

renormalizing the ZEUS data as described above. The fact that no E_T^{jet}-dependence is visible here can, of course, be explained by the fact that the resolved cross section falls more steeply with E_T^{jet} than the direct one [12]. Finally, we investigated whether these conclusions depended on the diffractive PDFs by comparing the results with resolved-only suppression of the 'H1 2006 fit B' to those obtained with the 'H1 2006 fit A' (last line in Tab. 3). Since the latter has a larger gluon density at large momentum fraction, the suppression had to be more important. The fit A results then tended to describe the high-E_T^{jet} H1 data and the ZEUS data slightly better, in particular in the $z_{I\!P}^{obs}$-distribution, which should be directly sensitive to the DPDFs, but the low-E_T^{jet} H1 data slightly worse. Unfortunately the experimental and theoretical errors are still too large to draw any strong conclusions.

While the epoch of HERA experiments has now ended and an International Linear Collider may not be built in the near future, it will be very interesting to investigate diffractive physics at the LHC. Suprisingly, proton-proton and heavy-ion collisions at the LHC can also be a source of high-energy photon collisions, and this may open up a whole new field of investigation for diffractive dijet photoproduction [41].

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